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Effects of Heavy Applications of Lime to Soils Derived from Volcanic Ash on the Humid Hilo and Hamakua Coasts, Island of Hawaii

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INTRODUCTION

The humid tropics provide an environment conducive to active alteration of geological material. Under this environment, volcanic ash with its high porosity and extensive specific surface area weathers rapidly. There is a heavy loss of silica and bases and an accumulation of iron and aluminum compounds. The resulting soils have a low content of crystalline clay minerals in the clay fraction, an acid reaction, and a low base status particularly in regard to calcium. Soils derived from volcanic parent material are of considerable agricultural importance in the humid tropics. Abundant sources of lime in the form of coral stone often occur in the vicinity of these acidic soils; thus, an understanding of the effects of lime application to such soils is desirable.

In their natural condition, the soils of the humid tropics support a dense vegetation. Lumber and other forest products are typical of the products obtained from such locations. Where the topography is favorable, the indigenous vegetation is often replaced by agricultural crops and pasture species. Modifications of these soils, which may include liming, are often necessary to obtain the most efficient production of the introduced pasture species.

In the temperate regions, liming has been intensively studied; at this stage, there is a fairly comprehensive knowledge of the effects of liming on the soils of these latitudes. Frequently, these studies have been conducted with soils having a high percentage of crystalline clay minerals in their clay fraction. Only sparse and fragmentary knowledge regarding the effects of liming in the humid tropics is available, and the existing information is often concerned with relatively light applications of lime.

The soils used in this study are derived from volcanic ash and are located on the humid Hilo and Hamakua coasts on the island of Hawaii, where they are used for growing sugar cane. A series of lime phosphate experimental plots was installed on the Hilo and Hamakua coasts, with the aim of increasing the yields of sugar cane. The high aluminum content and the low pH values of these soils present the possibility that toxic amounts

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of aluminum may be a limiting factor in plant growth. These soils are highly amorphous and have a high capacity to fix phosphates, thus making them sparingly soluble for plant use. It is suggested that benefit to sugar cane because of heavy liming of these soils is due either to the reduction of the toxic effects of aluminum or to improved phosphate availability.

The effects of heavy lime applications to these soils were investigated. To a lesser extent, the effects of phosphate applied as superphosphate within each lime level were considered.

LITERATURE REVIEW

1. Climate, weathering processes, and properties of soils derived from volcanic ash in the humid tropics

a. Climate

According to the Trewartha (*116*) system of climatic classification, the Hilo and Hamakua coasts on the island of Hawaii have a tropical wet climate. The two most distinguishing features of such a climate are uniformly high temperature and heavy precipitation distributed throughout the year so that there is no marked dry season.

b. Rock weathering and soil formation in tropical regions

As compared with the other regions, a more rapid rate of alteration of soil-forming materials is a feature of the humid tropics. This is due to the high moisture content of the soil and prevailing high temperatures which accelerate the rate of chemical reaction. The literature provides some generalizations concerning weathering in the tropics, and these usually present relationships between meteorological features and soil properties. Tanada (*111*) found that SiO_2/Al_2O_3 ratio decreases with increasing rainfall in Hawaiian soils. A similar relationship is reported by Prescott and Hoskins (*86*) for red basaltic soils from eastern Australia, by Martin and Doyne (*58, 59*) from Sierra Leone, and by Craig and Halais (*22*) from Mauritius. Harrison (*44*) conducted a number of detailed analyses concerning the alteration of igneous rocks in British Guiana. He concluded a great loss of silica was accompanied by an increase in aluminum when dolerite was weathered in British Guiana. The English term "dolerite" is equivalent to the American term "diabase." Gordon and Tracey (*36*) considered that a warm, more or less continuously moist subtropical to tropical climate in early Eocene time provided the ideal chemical environment for the formation of the Arkansas bauxite deposits. Sherman (*102*) stated that under an evenly distributed high rainfall the kaolinite clays decompose into their "free oxides." The "free oxides" in this case are the hydrated oxides of aluminum, especially gibbsite, and the iron oxide limonite. Mohr and van Baren (*69*) reported that the alteration of basic or intermediate rocks under good drainage conditions is accompanied by almost complete removal of silica and bases, and that there is an accumulation of hydrated aluminum compounds, limonite, a few unaltered fragments of feldspar, and, at times, secondary quartz.

c. Volcanic ash and rate of weathering of volcanic ash

Wentworth and Williams (*122*) defined volcanic ash as a pyroclastic rock whose fragments are less than 4 millimeters in diameter. Pyroclastic rocks are the products of explosive volcanic eruptions. By considering the rate of establishment of vegetation on areas where ash has been deposited, one may gain an understanding of the rapid rate of alteration of volcanic ashes. The catastrophic explosion of Krakatoa in 1883 completely destroyed all the flora of that island, according to Docters van Leeuwen (*25*). One year later, it was reported that only a few shoots of grass were present; but 3 years later, 26 species, including cryptogams, monocotyls, and dicotyls, were present. The 1951 eruption of Mount Lamington, Papua, described by Taylor (*113*), produced a volume of volcanic ash, and, in the process, partially or completely devastated an area of 90 square miles. Following the eruption, there was light rain and 3 days later a fungus appeared. Within 2 months, garden plants such as yams, taro, sweet potatoes, and bananas, were growing vigorously; previously, these plants had been established in native gardens. In the following months, grass grew, and trees became well established within the succeeding 2 years. This evidence indicates that the establishment of vegetation on freshly erupted volcanic ash is extremely rapid in the humid tropics; however, this phenomenon is not confined to this region but may occur in the temperate zone where it is more likely to proceed at a slower rate. The recovery of vegetation at Kodiak, which received about 1 foot of ash from the 1912 eruption of the Valley of Ten Thousand Smokes, is described by Griggs (*38*). This location is within 10 degrees of the Arctic Circle. A vigorous vegetation, mainly of species which had withstood an enforced dormancy, was established 3 years after the eruption. Grasses and berry bushes were included in this vegetation.

Genesis and formation of soils from volcanic ash in the humid climates of Grenada and St. Vincent, West Indies, have been described by Hardy *et al.* (*42, 43*).

d. Origin of parent material of soils of Hilo and Hamakua coasts

The parent material of the soils in this study is Pahala ash. Stearns and Macdonald (*108*) described Pahala ash as a late member of the Kahuku volcanic series of probably middle Pleistocene age. Macdonald (*55*) described this material as being made up of pumiceous glass fragments and composed mainly of mafic andesite. Pahala ash is widespread on the island of Hawaii, and among geologists there is some controversy concerning its main source. Because of the high rainfall and extensive weathering, it is difficult to determine the original composition and true source of the ash on the Hilo coast. Fraser (*34*), working with field evidence, considered that Kilauea volcano was the main source of this material. His contention is based on the observation of a systematic change that occurs outward from Kilauea. This change is concerned principally with a decrease in particle size and a decrease in thickness of layers. Stearns and Macdonald (*108*) indicated that the four volcanoes (Mauna Kea, Mauna Loa, Kilauea, and

Kohala) were general sources of Pahala ash, with Mauna Kea as the main source of the bulk of ash on Mauna Kea and also on the adjacent slopes of Mauna Loa.

e. Description of weathering condition of soils

The prevailing hot, humid climate of the Hilo and Hamakua coasts provides an environment for very rapid weathering of soil-forming materials. Hough *et al.* (*46*) recorded a heavy loss of bases and silica and accumulations of aluminum and iron for profiles of soils formed in this area. Tamura *et al.* (*110*) found approximately 30 percent allophane in the Akaka and Hilo series, two Hydrol Humic Latosols from this region. Weathering has advanced to such a stage that this material has been considered as a potential commercial source of aluminum by Sherman (*104*). In his study of Hydrol Humic Latosols from this region, Sherman (*103*) found that a mixture of light- and dark-colored aggregates is formed upon complete dehydration. Chemical analysis, differential thermal analysis, and X-ray diffraction techniques have shown the light-colored aggregates to be gibbsite. The dark-colored aggregates contain more than 20 percent silica and 30 to 40 percent iron oxide. Bates (*5*) contended that the high concentration of allophane along the Hamakua coast indicates that this amorphous mineral is a stage in weathering of the volcanic glass which is very widespread in the volcanic ash, and which occurs also in the matrix of the volcanic rocks. This worker also drew attention to the abundance of mineral material which occurs in quiet sections of streams in the high-rainfall regions of Hawaii. The Andosols in Java, described by Dudal (*27*), appear to have an origin and properties closely related to these Hawaiian soils.

2. Liming soils

a. Liming tropical soils

The main purpose of liming soils is to raise the pH of the soils. The general action follows the fundamental equation: $2H\text{-Clay} + CaCO_3 \rightleftharpoons Ca\text{-Clay} + CO_2 + H_2O$; the hydrogen of the cation exchange complex being replaced by calcium. Greene (*37*) reported that results from liming in the tropics have usually been unsatisfactory, and concluded that the whole question of liming tropical soils should be reconsidered. Richardson (*90*) emphasized extreme caution in liming tropical soils and mentioned the high probability of causing trace element deficiencies; he suggested as an alternative the selection of acid-tolerant agronomic crops. An application of 2 tons of lime to a Humic Ferruginous Latosol on the island of Maui produced a substantial increase in yield of forage and seed production for kaimi clover, according to Younge (*126*). Cassidy (*11*) suggested that the red earths on basalt andesitic tuff in Fiji are more likely to respond to liming than are recent volcanic ash soils. He and Harwood (*12*) reported that rice, sugar cane, and, particularly, pastures in Fiji responded to applications of 3 tons of coral sand per acre; and also, in a separate experiment, that 1 ton of ground calcium carbonate produced the same benefit as 2½ tons of ground coral stone.

b. Calcium status of Hawaiian soils

Hance (*39*) drew attention to the exceedingly low calcium content of Hilo coast soils and estimated that some of these soils had lost more than 99 percent of their original calcium content.

c. Rates of lime application

Rates of application of lime are dependent on the soil's buffering capacity, which is its ability to resist changes in pH. After conducting pot experiments with wheat, barley, maize, and clover, Chizhevskii and Korovkin (*16*) reported that lime requirements cannot be deduced from the pH of the salt extract of the soil, without considering also the exchange and hydrolytic acidity, base saturation, and available aluminum. Titration curves established by Matsusaka and Sherman (*62*) using 0.1 N NaOH have been used for calculating the lime requirements of Hawaiian soils.

d. Effects of heavy calcium additions

Heavy applications of lime, which are at times recommended, may raise the question as to whether large calcium increments may affect plant growth adversely. Loomis (*54*) reported that gypsum at the rate equivalent to 100,000 pounds per acre did not affect significantly the growth of corn and soy beans grown on an Iowa soil.

The adverse effects of overliming usually result in minor element deficiencies; however, Evans (*30*) considers that sugar cane is probably less prone to these deficiencies than any other tropical crop.

Younge and Otagaki (*128*) suggested that applications of 1 or 2 tons of lime to pasture areas on the island of Hawaii would shift the calcium-deficient forages above the critical level for most classes of beef cattle. Soils of the Akaka series were indicated to be in particular need of calcium.

3. Aluminum concentrations and toxicity

a. Soil acidity and aluminum toxicity

Soils which have very acidic pH values (below pH 5.0) have long been known to be generally less productive than soils with values closer to the neutral point. A limiting factor in very acidic soils could be a nutrient deficiency, probably calcium. With many of these soils, however, high concentrations of hydrogen ions or forms of aluminum that can affect plant growth adversely are considered the limiting factors for productivity. The aluminum ions and hydrogen ions may be simultaneously present in high concentrations, making it difficult to ascertain their separate effects; but it is generally believed that high concentrations of aluminum ions have a much more toxic effect on plant growth than high concentrations of hydrogen ions. Hardy (*40*) compiled an extensive account of soil acidity, with emphasis on tropical regions. He pointed out that where there was a deficiency of easily soluble nutrient bases, soil solutions may contain appreciable concentrations of ions of aluminum, iron, and manganese, either separately or together. When these concentrations rise above a critical level the soils will become appreciably infertile because of the toxicity of these ions in the soil solution. According to Scharrer and Schropp (*95*), the main reason for poor crop growth is the ease with which aluminum goes into solution from acid soils by base exchange reactions. Arnon and Johnson (*3*) found that, provided there were adequate nutrients, pH fluctuations from 4.0 to 8.0 were tolerated; only at pH 3.0 or at 9.0 was plant growth affected in an extremely adverse manner. Martin (*61*) reported that sugar cane plants grown in a nutrient solution maintained at pH 4.0 continued to make good growth during the 8 weeks of the experiment and no leaf symptoms of acid injury appeared. Chizhevskii and Korovkin (*16*) stated that soil acidity due to available aluminum was more harmful to wheat, barley, and clover, than was acidity due principally to exchangeable hydrogen. On the other hand, DeTurk (*24*) showed that red clover grew normally at pH 7.0 in sand cultures containing 160 ppm calcium but failed to grow at pH 5.0 in sand cultures at the same calcium level. Schmehl *et al.* (*97*) demonstrated that the rate of calcium absorption in alfalfa was greatly reduced in the presence of Al^{+++} and to a lesser extent with Mn^{++} and H^{+} in nutrient solution. It was suggested that the often-observed low-calcium content in plants grown on acid soils may be due to the antagonistic effect of Al^{+++}, Mn^{++}, and H^{+} on the absorption of Ca^{++}. Schofield (*98*) reported that for certain strongly acid soils high in sesquioxides the basic positive charges exceeded the permanent negative charge combined with the acidic negative charge. It was suggested that such soils retain anions but not cations. The basic positive charges occur in positions on the surfaces of sesquioxides; these positions are not charged when the hydrogen ion is dissociated, and positively charged when it is combined.

The combination of high acidity and of high contents of aluminum, mainly in an amorphous state, in these Hawaiian soils, presents the probability that aluminum may have a limiting effect on crop production. According to McGeorge (*64*), analytical evidence strongly indicated the presence of toxic amounts of aluminum in many Hawaiian soils. Several other workers have found that high concentrations of aluminum can affect plant growth adversely. Nondiffusible colloidal aluminum hydroxide was shown by McLean and Gilbert (*66*) and Trenel and Alten (*115*) to be definitely harmful when in contact with plant roots.

b. Mechanism of aluminum toxicity

Information concerning the actual mechanism of aluminum toxicity is meager. From studies with *Elodea*, *Spirogyra*, and *Lemna*, Fluri (*32*) reported that aluminum salts produce a plasmolysis of the protoplasm without any considerable contraction. Sergeev and Sergeeva (*100*) found that the beneficial effects of heavy phosphate applications to a soil containing soluble aluminum were due to the physiological antagonism of these ions in the plant. Plasmolysis measurements of the epidermis of fleshy scales of an anthocyanin-bearing onion showed that the viscosity of the protoplasm was increased by aluminum and decreased by phosphate. Hoffer and Carr (*45*) found that corn plants containing the largest quantities of iron and aluminum appeared to develop the severest cases of root rot under conditions favorable for maximum growth of the responsible organism. The effects of additions of aluminum salts to excised root hairs were studied by Addoms (*1*). She reported a flocculation of the protoplasm. Wright (*125*) recorded the internal precipitation of phosphorus by aluminum within the plant tissue. He concluded that the interference of aluminum with the uptake and translocation of phosphorus is the main cause of aluminum toxicity. Coleman *et al.* (*21*) stated: "The mechanism of aluminum toxicity is not known."

c. *Nature of aluminum ions*

A comprehensive study of aluminum ions and their reactions has been made by Brosset (*7, 8*). Starting from very acidic reaction values, soluble Al^{+++} ions change to complex hydrolyzed and polymerized forms with increased pH values. Raupach (*89*) considered that aluminum ions of varying valence may be involved as the pH of the soil rises. The colloidal properties and amphoteric nature as related to aluminum toxicity have been studied by Mattson and Hester (*63*). Jones (*49*) conducted experiments which showed aluminum is present in fly-ash at high pH values, and it is available to plants grown in the ash. His studies were concerned with some of the problems of reclamation of pulverized coal-ash (fly-ash) deposits from industrial areas in England. The problem of how plants could absorb aluminum in the anionic form was discussed, and it was suggested that organic acids produced by the plants may act as chelating agents which prevent precipitation at physiological pH values. This hypothesis was used as a basis for an explanation of the different responses exhibited by various ecological groups of plants to excesses of aluminum.

Pioneer work concerning soluble aluminum content in relation to soil reaction was conducted by Magistad (*56*). Soil energy of adsorption of hydrogen was reported by Chernov (*15*) to be much less than soil energy of adsorption of aluminum. Paver and Marshall (*79*) stated that in an acid soil aluminum acts as an exchangeable base and may occupy the greater number of the exchange positions in such soils. Lin and Yu (*53*) concluded that aluminum is almost entirely responsible for the acidity of krasnozems.

d. *Determination of aluminum values*

A number of terms have been used for the component of soil aluminum that is directly concerned with soil acidity and with any related limiting effect on plant growth. The terms "mobile" and, less commonly, "easily soluble," both frequently used by Russian and European workers, are probably the same as "soluble" or "water soluble." The term "active" aluminum has been used by many workers from different localities; but while the term is descriptive, lack of clarity concerning its exact meaning limits its value for comparison purposes. A number of "extractable" aluminum values have been reported in the literature, and the methods of extraction have usually been included with the reports. A number of workers have determined "exchangeable" aluminum; such investigations are based on titrations using

KOH or NaOH. The work of Chernov (*15*), who found that titratable acidity of KCl extracts of Podsols and red soils was equal to the aluminum content of the soils, provided the basis for such methods. The presence of aluminum in the solution was due to the exchange between potassium cations and aluminum cations adsorbed on the soil colloids. Although there are numerous methods of determination and numerous terms for aluminum, the trends of the values in a great majority of situations are similar. A critical level for aluminum values occurs at pH 5. Soils with a pH below this value often have considerably higher aluminum values than soils with a pH value slightly in excess of 5.

e. Acid sulphate (cat clay) soils

Acid sulphate soils were first studied in the temperate zone by Van Bemmelen (*118*). They usually occur on marine flood plains, and are characterized by high sulphate content and extremely high potential acidity. Drainage produces the oxidized or cat clay form and promotes the production of sulphuric acid, which results in extremely low pH values and extremely high aluminum values. These soils with their high aluminum content or potentially high aluminum content are widespread in the tropics and often occupy a considerable area. Examples of acid sulphate soils have been described for Vietnam (*71*), Thailand (*81*), East Pakistan (*117*), Borneo (*120*), tropical Africa (*14, 26*), and Surinam (*73*).

Up to the present time, these acid sulphate soils with their special aluminum toxicity problems have been utilized only to a limited extent; but with the rapidly expanding world population, increasing utilization of such soils may well be anticipated; thus the work at Vietnam (*4, 71*) is of great importance. According to Auriol and Lam-Van-Vang (*4*), aluminum toxicity is the most prominent feature of acid sulphate soils, under conditions prevailing in Vietnam. Sugar cane and some rice varieties grown there are highly susceptible to aluminum toxicity, according to Moormann (*71*). Specially selected rice varieties are grown on the acid sulphate soils, and on the medium acid sulphate soils sugar cane often shows a poorly developed root system in the compacted clays. This worker considered the best method of reclamation for such soils is to combine liming with careful and progressive drainage aimed at gradually releasing and neutralizing the potential acidity. Evidence indicates that the pH values upon oxidation of these sulphate clay soils provide an indication of whether reclamation would be worthwhile. At present when such pH values are 3.5 or less such soils are not cultivated.

Moormann (*71*) also pointed out that normally productive areas may have serious losses in yield due to aluminum toxicity of inundation waters which have been in contact with acid sulphate soils.

f. Aluminum content of plants

Bertrand and Levy (*6*) studied a great number of plants, including various vegetables, and concluded that aluminum exists in all flowering plants in widely varying amounts. Levy (*52*) found that all 75 specimens of phanerogams that she studied contained aluminum, and that the aluminum accumulated more rapidly in early stages of growth than later.

The relative tolerance of crop plants to aluminum was studied by McLean and Gilbert (*65*), and they found dwarfing and root injury were the first effects of aluminum toxicity. Olsen (*78*) published a list of lime-loving and lime-hating plants and discussed the relationships between lime, soil acidity, and aluminum toxicity.

Robinson and Edgington (*92*) reported a number of alumina-accumulating plants mainly from the U.S. mainland. Accumulation of aluminum in the Australia–New Guinea flora is described by Webb (*121*). An exceptionally high accumulation of aluminum in Australian silky oak is recorded by Smith (*106*).

The aluminum content of some Hawaiian plants has been published by Moomaw *et al.* (*70*). The plants were obtained principally from acidic soils which were known to have a high aluminum content. Pteridophytes with aluminum values of 3,000 to 9,000 ppm were prominent. However, values in excess of 1,000 ppm for some common grasses such as rattail grass (*Sporobolus capensis*) and rice grass (*Paspalum orbiculare*) were reported for the first time.

Sommer (*107*) conducted a series of experiments attempting to prove the essential nature of aluminum. He obtained an increase in amount of seed and a small increase in total dry weight of pea cultures with aluminum additions. A large response to aluminum, expressed in dry weight by millet, was also obtained and it was suggested that this element may be essential for this plant. Taubock (*112*) took great care to exclude aluminum from a series of solution culture experiments, but the 124 varieties of flowering plants that he studied showed no lack of aluminum, even in the second generation. However, culture of pteridophytes was unsuccessful under the same conditions, and the lack of aluminum was manifested in cessation of growth within a few weeks followed by a progressive necrosis. Pellet and Fribourg (*80*) reported a very low aluminum content in sugar cane.

Hoffer and Carr (*45*), with a series of injections, established a definite cumulative toxicity of aluminum within corn plants. They suggested that the same phenomenon occurs naturally in the field. A series of excellent photographs illustrating the accumulation of aluminum and iron in basal tissues of unthrifty corn plants is included in Hoffer and Carr's publication. These plants had usually been produced on highly acidic soils.

4. Phosphate additions and modifications

a. General behavior of phosphate additions and soil phosphate

The condition of soil phosphate is greatly influenced by the presence and forms of calcium and aluminum compounds. Additions of phosphate to acidic soils usually reduce the content of mobile aluminum. In some instances, the beneficial effect of phosphate fertilizers could be attributed, partially at least, to reduction of available aluminum. Liming generally improves the availability of phosphates.

In his studies with red soils, Nakaidze (*77*) found that liming increased the effect of phosphate fertilizers on growth of buckwheat and corn. Phosphate fertilizers added to limed soils 1 month before planting had a greatly reduced effect compared with that of fertilizers added immediately before planting. The increased phosphate mobility was attributed chiefly to the coagulation of the sols of $Al(OH)_3$ and $Fe(OH)_3$. Ratner (*88*) showed that by supplying sufficient phosphate for plants, the mobile aluminum did not interfere with the yield. It was noted that large quantities of phosphorus as well as aluminum are absorbed when no phosphorus was added. It was considered that precipitation of phosphates by aluminum in plant tissues caused phosphate starvation.

The effects of calcium on the distribution of phosphorus in aqueous systems were studied by Naftel (*74*), who found calcium phosphates occurred as follows: monobasic at pH 3.0 to 5.0, dibasic at pH 5.0 to 6.4, and tribasic above pH 6.4. It appeared that liming acid soils causes a decrease in available phosphorus by increasing the absorption of phosphorus by the soil colloids, but only on soils of high SiO_2/R_2O_3 ratio. The absorption of phosphate by colloids of low SiO_2/R_2O_3 ratio was practically unaffected by calcium.

Pierre and Stuart (*83*) obtained a reduction of aluminum in soil solution, without any change in the pH, by using heavy (2,000 pounds P_2O_5 per acre) applications of superphosphate. The heavy phosphate applications were considered to reduce injurious effects of aluminum by precipitating aluminum in the soil and in the plant tissue. The increased productivity due to added phosphate was considered to be due to increased mobility of phosphate in the soil and in the plant. In view of the very heavy calcium additions in these experiments it is of great interest to encounter a somewhat different viewpoint. According to Ratner (*87*), any appreciable chemical union of aluminum and phosphate can take place only in a soil saturated with calcium. In an acid environment with high soluble aluminum content, a precipitation of phosphate in the beet plant was observed by Wright (*124*), who found that this reduced the availability of phosphorus for utilization by the plant.

According to Melville (*67*) and Woodcock (*123*), liming greatly increased the efficiency of phosphate fertilizers, particularly superphosphate, on the growth of New Zealand pastures. Saunders (*94*) contended that the "active" aluminum in a New Zealand soil produced from andesitic volcanic ash is derived from amorphous allophane. It was concluded from pH-phosphate retention curves that fixation of added phosphorus was due to "active" aluminum and not exchangeable calcium.

Davis (*23*) reported that relatively small increases in cation exchange capacity due to additions of monocalcium phosphate were dependent on the amount of added phosphate.

b. Tropical conditions

The availability of phosphorus in most lateritic soils in the tropics is increased by liming, according to Koch (*51*).

A liming-phosphate experiment with an acidic soil was conducted by Schroo and Schmidt (*99*) in Trinidad. Sugar cane plants were grown to maturity in 40-gallon oil drums. It was noticed that the root tips were severely damaged in nonlimed soils. Such damage, called "club-tip," was considered to be possibly due to toxic effect of aluminum. Liming increased by 10 percent the total sugar produced by the cane. Although there were small responses to phosphate in the absence of lime, it was concluded that the only real need of this soil was lime. Younge and Moomaw (*127*) considered that the stripsoil culture on bauxite land on Kauai requires a phosphorus treatment of about 600 pounds phosphorus per acre compared to 300 pounds phosphorus for the topsoil. Chu and Sherman (*17*) reported that Hawaiian soils fix as much as 90 percent of added phosphate in the presence of hydrated iron and aluminum oxides. In these experiments the maximum rate of phosphorus used was 10,000 ppm. The maximum fixation occurs below pH 4.0 and the minimum fixation occurs at neutral or alkaline pH values.

5. Leaching studies

Studies in leaching losses have been concerned principally with retention of calcium with liming practices (*101*), particularly in regard to sandy soils (*2*). Joffe (*48*) studied the movement of cations in a gray-brown podsolic soil. These experiments, which were usually carried out on a long-term basis, have produced considerable understanding of the mechanism and products of leaching. However, it may be pointed out that virtually all the information concerning leaching losses from soils has been obtained from experiments in the temperate zone with soils from the same latitudes. The clay mineral fraction of such soils usually consists of crystalline clay minerals. Seasonally fluctuating temperatures would be of importance, and thus this information is of limited value when interpreting leaching losses from heavily limed and unlimed, highly amorphous soils.

Magistad (*56*) found that the curve for solubility of aluminum in the soil solution at various pH values almost coincided with the curve for the solubility in water at the same reactions. At the neutral point there was practically no soluble aluminum. There was a substantial increase as pH value dropped below 5.0, and at pH 4.5 the amount of soluble aluminum increased very rapidly.

Pierre *et al.* (*82*) indicated that high concentrations of soluble salts were associated with high contents of soluble aluminum. On the other hand, at a given pH, soils with high organic matter content were associated with low soluble aluminum values and soils with a low organic matter content were associated with high soluble aluminum values. Naftel (*75, 76*) found that added lime more than doubled the amount of soluble phosphate. Exchangeable manganese was replaced directly with the amounts of added lime.

In their studies of podsolic illuvial horizons, Martin and Reeve (*57*) studied the flocculation of humus from an Australian Podsol, at carbon-aluminum ratios of 16, and found complete precipitation of carbon and aluminum occurred only at pH 4.0 to 4.5. As the pH was increased above 4.5, almost all the added carbon and aluminum remained unflocculated. No precipitation was found with any pH used with carbon-aluminum ratios of 20 or more. In the Amazon Valley, clear water free of aluminum with a pH of 5.2 was reported by Sioli (*105*). Black water, with a pH of 4.1 and which came from forested podsolic areas in the same vicinity, contained aluminum. The color difference in the waters was due to the degree of oxidation of the organic matter.

In his comprehensive study of silica and silicates, Iler (*47*) stated: "There is considerable evidence that silica can exist in solution in water in the monomeric form, presumably hydrated as monosilicic acid, $Si(OH)_4$, or, if the pH is high enough, as silicate ions." However, this worker considered that the mechanism by which silica is dissolved and deposited is still largely a matter of speculation.

Mink (*68*) reported that the composition of the fresh-water lens of southern Oahu is rather uniform. The absence of variation in the composition suggested an independence of location and time of residence in the basalt environment. Fresh ground water from the aquifer of southern Oahu had modal values of: Ca, 8 ppm; SiO_2, 36 ppm; and PO_4, 0.20 ppm.

6. Sugar cane plant and plant analysis

There are many excellent sources of scientific information concerning the production of sugar cane in the tropics. The principal reason for this situation is the widespread economic importance of this crop.

A comprehensive description of physiology, growth, nutrition, and chemical composition is included in *Botany of Sugar Cane* by Van Dillewijn (*119*). The mineral nutrition of all elements excepting N, P, and K has recently been described by Evans (*30*). The distribution and range in concentration of mineral elements in stem tissues is an important inclusion in this publication. An account of mineral nutrition for sugar cane under Hawaiian conditions is presented by Burr *et al.* (*10*). They found that the sensitivity of sugar cane varieties to environment is of such importance that cane breeders have devoted much attention to producing varieties highly suited to each locality. Root temperatures below 70°F. become strongly limiting to growth. The "crop-logging" procedure for Hawaiian sugar cane, as described by Clements (*18*), includes values for phosphorus and calcium in sugar cane tissue. The study by Goodall and Gregory (*35*) of plant composition as a nutritional index includes values for sugar cane.

Martin (*60*) grew sugar cane plants in culture solutions from which calcium had been omitted. A marked retardation of growth and a slight chlorosis of the leaves developed within 3 to 4 weeks. Minute spots, which first developed on older leaves, increased with the age of the leaves; the spots developed dead centers and the necrotic areas soon coalesced; the innermost leaves failed to make growth and the spindle died. Root development was greatly retarded 3 weeks after calcium had been omitted from the nutrient solution. The roots became soft and flaccid as a result of *Pythium* root rot; but when the rapidly dying plants were placed in a plus-calcium solution, an immediate growth response resulted. Since the terminal bud had died in each plant, lateral buds began to develop shoots of normal color and growth.

In their investigations of chemical composition of Hawaiian pastures, Edwards and Goff (*29*) studied location, plant species, and season. They found calcium and phosphorus values were low for pasture grass species in the wet windward section of Parker Ranch on the island of Hawaii.

Younge and Otagaki (*128*) found evidence of definite forage phosphate deficiencies in many areas on the island of Hawaii. Acute phosphorus deficiencies were found in the soils of both the Olaa and Akaka series. The absence of visual calcium deficiency symptoms in Hawaiian cattle was thought to be due to masking by the more acute protein deficiency, which can slow the growth of cattle to levels where calcium is adequate, or to the fact that the cattle may not be in calcium-deficient areas.

MATERIALS AND METHODS

Field plot experiments

This study was made on soils from a series of lime-phosphate replicated field plot trials, planned by Dr. H. F. Clements of the University of Hawaii, and conducted on sugar plantations of C. Brewer & Co., Ltd., on the Hilo and Hamakua coasts on the island of Hawaii.[2] Sugar cane was being grown in these experimental plots. It was intended that the experiment should continue for one plant crop and one ratoon crop, or a duration of 4 to 6 years.

Lime applications: Three levels of lime, added in the form of crushed coral stone, were applied for each experiment, as indicated in table 1. These liming values were determined from buffer curves after the pH values of some collected field samples were obtained. The highest lime applications were anticipated to produce a pH of 7.0.

Phosphate treatments: The phosphate additions were in the form of superphosphate. Gypsum in quantities that would equalize the calcium of the highest superphosphate treatment was added to all treatment plots. The possibility of studying calcium as a nutrient was thus eliminated.

Meteorological data: The rainfall isohyetal map of the island of Hawaii, on which the locations of the experimental field plots have also been indicated, is presented in figure 1. Rainfall and temperature data for the plots are presented in tables 2 and 3. Rainfall data for the plantation at Hilo are

[2] The experimental plans and treatments, the plant analysis data, as well as the actual yield data from all these experiments were published as follows:
Clements, H. F. 1962. The Coral Stone-Phosphate Experiments on the Hilo and Hamakua Coasts. 1961 Repts., Hawaiian Sugar Tech. 20th Ann. Meeting. Pp. 77–105.
Clements, H. F. 1963. Factors Determining the Response of Sugar Cane to Calcium Carbonate in Hydrol Humic Latosols. Proc. 11th Congr. Internatl. Soc. Sugar Cane Tech., Mauritius, 1962. Pp. 140–161.

TABLE 1. Rates of lime application to experimental field plots in soils of the Hilo series, Akaka series, and Kaumoali series, on the island of Hawaii

SOIL SERIES	PLANTATION	CRUSHED CORAL STONE. POUNDS PER ACRE
Hilo	Hilo	0
		4,000
		11,000
		22,000
Akaka	Hakalau	0
		4,000
		11,000
		22,000
	Pepeekeo	0
		4,000
		19,000
		34,000
Kaumoali	Paauhau	0
		12,000
		30,000
		46,000

from records of a recording station at 150 feet elevation; means are for a period of 64 complete years. For the plantation at Pepeekeo, records are from a station at 900 feet elevation, and means are for a period of 10 complete years. Both of these recording stations are reasonably close to the respective field experimental plot area for each plantation; such is not the case for the Hakalau experimental plot area, but mean annual rainfall for this location is considered to be only slightly lower than that for the Pepeekeo experimental area. Comparable rainfall data for Paauhau are from a station at 1200 feet elevation, which is the closest to the experimental field plots on this plantation; means are for a period of 9 complete years. Rainfall information (table 2) and the isohyetal map (fig. 1) were obtained from a Hawaii Water Authority publication (*109*).

Figures for the temperature readings for the plantation at Hilo are from records made at 40 feet elevation; means are for a period of 50 years. Figures for the readings at Hakalau Mauka have not been completely processed,

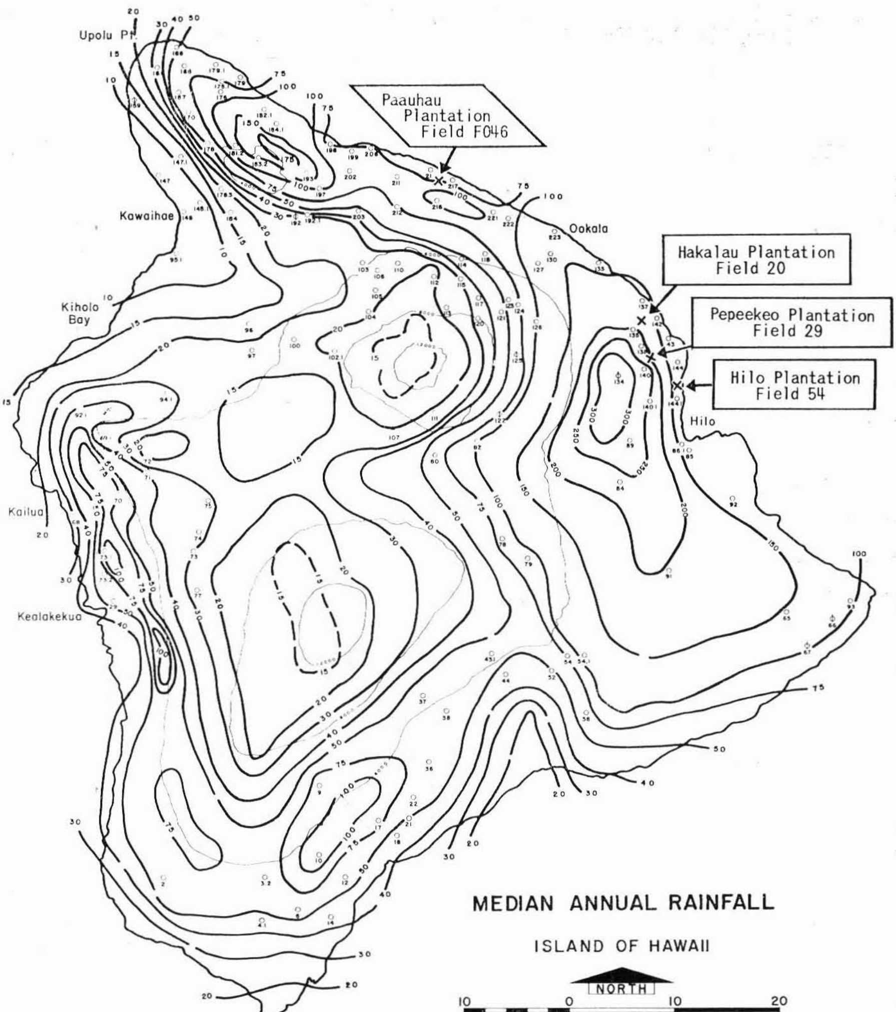

FIG. 1. Map of island of Hawaii, showing median annual rainfall isohyets and location of experimental field plots. (*Source:* Hawaii Water Authority.)

so only those for 1959 and 1960 are presented; they are from records supplied by the experiment station of the Hawaiian Sugar Planters' Association.

Field plots: Plot size was consistent within each experimental area, but plot sizes varied slightly from plantation to plantation. Each plot was approximately 0.05 acre and consisted of eight rows of sugar cane.

Descriptions of the soil series and plot locations used in this study are as follows:

TABLE 2. Median monthly rainfall (in inches) for Hilo, Pepeekeo, and Paauhau plantations, island of Hawaii

MONTH	MEDIAN MONTHLY RAINFALL IN INCHES		
	Hilo, 150 feet	Pepeekeo, 900 feet	Paauhau, 1200 feet
January	8.6	12.7	6.2
February	8.6	14.3	7.6
March	13.1	18.7	13.7
April	12.0	12.1	5.4
May	8.8	16.0	3.3
June	6.9	7.2	1.4
July	10.6	12.7	3.2
August	11.8	13.0	4.3
September	8.2	7.1	1.6
October	9.9	13.2	4.2
November	14.1	15.5	6.7
December	13.4	21.3	6.5
ANNUAL RAINFALL MEDIAN	139.0	183.5	67.8

Hilo series: The experimental area for the soils of the Hilo series was at an elevation of 150 feet on Hilo plantation, on a moderately uniform slope with an aspect towards the Pacific Ocean. Field plots were installed in field No. 54 on February 11, 1959. The previous fertilizer history for soils of the Hilo series from Hilo plantation field No. 54 is presented in table 4.

Akaka series: Two experimental areas for the soils of the Akaka series were employed. One of these areas was at an elevation of 800 feet on Hakalau plantation, on a moderate slope towards the Pacific Ocean with a rather steep slope towards the south. The sugar cane variety was 49-5. Field plots were installed in field No. 20 on January 27, 1959. The other area was at 900 feet elevation on Pepeekeo plantation, on a moderately uniform slope towards the Pacific Ocean. The sugar cane variety was 44-3098. Field plots were installed in field No. 29 on June 9, 1959. The previous fertilizer histories for soils of the Akaka series from Hakalau plantation field No. 20 and from Pepeekeo plantation field No. 29 are presented in tables 5 and 6, respectively.

Soils of both the Hilo and Akaka series belong to the Hydrol Humic Latosol group and have developed from volcanic ash. They have been described by Cline *et al.* (*19*).

TABLE 3. Monthly mean maximum and mean minimum temperature for Hilo and Hakalau plantations, island of Hawaii

MONTH	HILO, 40 FEET		HAKALAU MAUKA, 800 FEET			
	Max. °F. (50-year period)	Min. °F. (50-year period)	Max. °F. 1959	Max. °F. 1960	Min. °F. 1959	Min. °F. 1960
January	78.1	62.9	77.2	74.5	60.3	57.3
February	78.4	62.7	74.0	76.0	59.4	58.0
March	77.9	63.2	77.5	76.1	59.7	58.3
April	78.6	64.3	77.5	74.8	60.9	60.8
May	80.4	65.3	78.1	79.1	61.2	61.4
June	81.5	66.5	82.3	80.5	62.1	61.5
July	81.9	67.5	82.6	81.0	62.8	63.0
August	82.7	68.2	81.9	79.9	64.9	62.8
September	82.6	67.6	80.9	80.2	63.7	62.5
October	82.1	67.1	82.2	80.5	62.0	62.6
November	80.4	65.7	77.2	77.2	62.6	66.4
December	78.8	64.0	73.3	78.2	60.2	58.4

TABLE 4. Previous fertilizer history for soils of the Hilo series, field No. 54, Hilo plantation, island of Hawaii

YEAR	APPLICATION, POUNDS PER ACRE		
	P_2O_5	CaO	K_2O
1952	44	0	242
1954	291	310 (super)	335
1956	111	155 (super)	311
1959	347	478 (UA No. 1)	429

TABLE 5. Previous fertilizer history for soils of the Akaka series, field No. 20, Hakalau plantation, island of Hawaii

YEAR	APPLICATION, POUNDS PER ACRE		
	P	K	CaO
1952	179	321	226
1954	155	368	195
1956	126	254	158
1958	257	416	354

TABLE 6. Previous fertilizer history for soils of the Akaka series, field No. 29, Pepeekeo plantation, island of Hawaii

YEAR	APPLICATION, POUNDS PER ACRE			
	N	P	K	CaO
1952	191	50	280	0
1954	250	120	422	0
1956	338	446	474	0
1959	345	203	425	530
1961	284	396	415	0

Kaumoali series: The experimental area for the soils of the Kaumoali series was at an elevation of 1,500 feet on Paauhau plantation, on a moderately uniform slope towards the Pacific Ocean. The location was adjacent to a bitumen-topped road. Some fragments of glass and crockery were visible in the field plots, and it is possible that the location may have formerly been the site of either a dwelling or a rubbish dump. Field plots were installed in field No. F046 on April 10, 1961. The previous fertilizer history for soils of the Kaumoali series from Paauhau plantation field No. F046 is presented in table 7.

TABLE 7. Previous fertilizer history for soils of the Kaumoali series, field No. F046, Paauhau plantation, island of Hawaii

YEAR	ROTATION	APPLICATION, POUNDS PER ACRE			
		N	P	K	CaO
1952	plant	192	390	272	579
1954	1st ratoon	208	—	347	—
1956	2nd ratoon	316	23	528	—
1959	plant	308	413	410	679

In a private communication from local soil conservation officers, the Kaumoali series was listed as a tentative series, subject to review and approval. It is a Humic Latosol developed on volcanic ash. This area had formerly been mapped as the Kukaiau series.

Collection of soil samples: Soil samples representative of the field plots were collected and kept in firmly tied polyethylene bags in order to retain their field-moist condition. In dealing with highly hydrated amorphous soils, this has been a regular practice of the Department of Agronomy and Soil Science, University of Hawaii. The principal reason for this practice is to avoid the substantial reduction in cation exchange capacity which occurs with dehydration, as reported by Kanehiro and Sherman (*50*).

Analytical methods

A Beckman pH meter was employed to obtain pH readings, using a 1:1 soil-water mixture, which had stood for 24 hours with occasional stirring. Cation exchange capacity was measured using normal ammonium acetate adjusted to pH 7.0, as described by Piper (*84*). Calcium was determined by precipitating as calcium oxalate and subsequently titrating with standard potassium permanganate.

Ammonium acetate–barium chloride solution adjusted to pH 4.8 was used as an extracting medium for aluminum; sufficient barium chloride was used to make this solution 0.2 N in barium ions. Fifty ml. of this solution were left in contact with 10 gm. of soil for approximately 16 hours. This material was then filtered through a Büchner funnel using additional amounts of the extracting solution until a total volume of 100 ml. was obtained.

The colorimetric analysis of aluminum using thioglycollic acid as an inhibitor for iron, according to the method described by Chenery (*13*), was followed with a few modifications. A suitable aliquot, usually 1 ml., was taken from the extracted solution and 20 ml. of water were added to it. Two ml. of 1:100 thioglycollic acid were then added to reduce the ferric iron to the ferrous state; in this latter state, the ferrous iron does not interfere with the development of aluminum color. Next, 10 ml. of the "aluminum reagent" were added, and, finally, using dilute hydrochloric acid and dilute ammonium hydroxide, the pH of this mixture was adjusted to pH 4.8. The mixture was transferred to a 50 ml. standard flask and heated in a boiling water bath for 16 minutes. The flask and contents were removed from the water bath, cooled for 1½ hours, and then the contents were made up to volume and read in a Klett-Summerson colorimeter, using a green filter.

As these soil samples were in a moist condition, it was necessary to obtain a moisture factor in order to calculate results on an oven-dry basis.

EXPERIMENTAL RESULTS AND DISCUSSION

Short-term effects of treatment on test soils

Results

The Hilo experimental plots were installed on February 11, 1959, and sampled 21 weeks later. The results of the chemical analysis of these soils are presented in table 8. Comparing the values from control plots with those from plots receiving the heaviest lime applications, the exchangeable calcium values ranged from 1.94 to 16.86 me. per 100 gm.; and extractable aluminum, from 10.74 to 7.13 me. per 100 gm. Applied lime did not directly affect cation exchange values. A significant increase (table 9) in cation exchange capacity was obtained with each level of applied phosphate in the plots receiving 22,000 pounds lime per acre. The pH range was from 5.4 to 6.3.

TABLE 8. Cation exchange capacity, pH, exchangeable calcium, and extractable aluminum (mean values of two samples) for various lime and phosphate levels added to soils of the Hilo series, Hilo plantation, island of Hawaii

CORAL, lb/acre	P_2O_5, lb/acre	pH	CATION EXCHANGE CAPACITY, me/100 gm	EXCHANGEABLE Ca, me/100 gm	EXTRACTABLE Al, me/100 gm
0	0	5.4	53.4	1.94	10.40
0	200	5.4	44.7	2.58	9.58
0	400	5.4	47.2	2.20	10.74
4,000	0	5.5	45.8	3.52	7.92
4,000	200	5.6	50.3	4.68	8.49
4,000	400	5.5	46.6	4.61	7.82
11,000	0	6.0	47.3	9.00	7.15
11,000	200	5.8	50.2	7.02	9.02
11,000	400	5.9	44.2	9.34	7.21
22,000	0	6.2	45.8	15.46	7.35
22,000	200	6.3	50.6	16.86	8.02
22,000	400	6.2	54.6	15.58	7.13

TABLE 9. Effects of phosphate applications on cation exchange capacity in the Hilo series plots receiving 22,000 pounds lime per acre; and on the exchangeable calcium values in the Akaka series plots receiving 34,000 pounds lime per acre, island of Hawaii

APPLIED P_2O_5, POUNDS PER ACRE	HILO SERIES PLOTS, HILO PLANTATION, RECEIVING 22,000 POUNDS LIME PER ACRE	AKAKA SERIES PLOTS, PEPEEKEO PLANTATION, RECEIVING 34,000 POUNDS LIME PER ACRE
	Cation exchange capacity, me/100 gm	*Exchangeable Ca, me/100 gm*
0	45.8[a]*	28.44[a]
200	50.6[b]	19.72[b]
400	54.6[c]	13.42[c]

*Where different letters are used, the values differ significantly according to Duncan's (*28*) multiple range test.

The Hakalau experimental plots were installed on January 27, 1959, and sampled 23 weeks later. The results of the chemical analysis of these soils are presented in table 10. Comparing the values from control plots with those from plots receiving the heaviest lime applications, the exchangeable calcium values ranged from 0.54 to 15.22 me. per 100 gm., and extractable aluminum, from 15.44 to 8.89 me. per 100 gm. Liming applications did not directly produce any modifications in the cation exchange capacity, which varied from 60.2 to 69.5 me. per 100 gm. The pH range was from 4.6 to 6.0.

TABLE 10. Cation exchange capacity, pH, exchangeable calcium, and extractable aluminum (mean values of two samples) for various lime and phosphate levels added to soils of the Akaka series, Hakalau plantation, island of Hawaii

CORAL, lb/acre	P_2O_5, lb/acre	pH	CATION EXCHANGE CAPACITY, me/100 gm	EXCHANGEABLE Ca, me/100 gm	EXTRACTABLE Al, me/100 gm
0	0	4.8	63.6	1.08	15.44
0	200	4.6	67.8	0.79	15.00
0	400	4.6	63.5	0.54	14.83
4,000	0	5.2	60.2	3.42	13.66
4,000	200	5.0	64.2	3.66	13.92
4,000	400	5.3	68.5	3.70	14.84
11,000	0	5.5	64.4	10.48	10.97
11,000	200	5.4	64.3	7.17	11.90
11,000	400	5.6	69.5	9.04	11.69
22,000	0	6.0	64.5	13.00	10.47
22,000	200	6.0	69.4	15.22	8.89
22,000	400	5.8	68.2	13.62	10.48

The Pepeekeo experimental plots were installed on June 9, 1959, and sampled 12 weeks later. The results of the chemical analysis of these soils are presented in table 11. Comparing the values from control plots with those from plots receiving the heaviest lime applications, the exchangeable calcium values ranged from 0.72 to 28.44 me. per 100 gm., and extractable aluminum, from 17.85 to 10.06 me. per 100 gm. A significant decrease (table 9) in exchangeable calcium was obtained with applied phosphate in the plots receiving 34,000 pounds lime per acre. Neither lime nor phosphate produced any significant change in cation exchange capacity, which varied from 53.9 to 77.3 me. per 100 gm. The pH range was from 5.0 to 6.4.

TABLE 11. Cation exchange capacity, pH, exchangeable calcium, and extractable aluminum (mean values of two samples) for various lime and phosphate levels added to soils of the Akaka series, Pepeekeo plantation, island of Hawaii

CORAL, lb/acre	P_2O_5, lb/acre	pH	CATION EXCHANGE CAPACITY, me/100 gm	EXCHANGEABLE Ca, me/100 gm	EXTRACTABLE Al, me/100 gm
0	0	5.0	53.9	0.99	16.09
0	200	5.4	64.6	1.64	15.66
0	400	5.0	68.7	0.72	17.85
4,000	0	5.6	66.8	3.61	14.66
4,000	200	5.7	77.3	3.63	14.57
4,000	400	5.5	63.3	2.90	13.87
19,000	0	6.0	61.6	11.19	12.96
19,000	200	6.1	58.2	11.72	11.93
19,000	400	6.2	71.2	10.72	13.72
34,000	0	6.4	68.4	28.44	10.06
34,000	200	6.2	67.6	19.72	11.21
34,000	400	6.2	66.4	13.42	12.43

The Paauhau experimental plots were installed on April 10, 1959, and sampled 22 weeks later. The results of the chemical analysis of these soils are presented in table 12. Comparing the values from control plots with those from plots receiving the heaviest lime applications, the exchangeable calcium values ranged from 1.16 to 32.07 me. per 100 gm., and extractable aluminum, from 22.78 to 13.20 me. per 100 gm. In the plots which had received 30,000 pounds lime per acre, those receiving 400 pounds phosphorus per acre showed a significant increase in exchangeable calcium when compared with plots receiving the other levels of applied phosphate. This relationship is shown in table 13. Neither lime nor phosphate produced any significant change in cation exchange capacity, which varied from 55.4 to 63.7 me. per 100 gm. The pH range was from 4.7 to 6.0.

The relationship between exchangeable calcium and extractable aluminum for soils of each experimental plot area is illustrated in figure 2. The correlation coefficients for these relationships are presented in table 14. The correlation coefficients and regression factors for the relationships between soil pH and logarithm of exchangeable calcium are presented in table 15. The correlation coefficients and regression factors for soil pH and extractable aluminum are presented in table 16. In calculating the regression values, x = pH value.

TABLE 12. Cation exchange capacity, pH, exchangeable calcium, and extractable aluminum (mean values of two samples) for various lime and phosphate levels added to soils of the Kaumoali series, Paauhau plantation, island of Hawaii

CORAL, lb/acre	P_2O_5, lb/acre	pH	CATION EXCHANGE CAPACITY, me/100 gm	EXCHANGEABLE Ca, me/100 gm	EXTRACTABLE Al, me/100 gm
0	0	4.7	61.4	1.16	22.78
0	200	4.9	58.0	1.50	21.45
0	400	4.9	59.9	1.82	22.40
12,000	0	5.4	59.1	7.58	17.84
12,000	200	5.2	63.7	5.30	19.39
12,000	400	5.3	58.6	6.44	19.45
30,000	0	5.5	55.4	12.00	17.49
30,000	200	5.4	62.8	12.81	17.86
30,000	400	6.0	58.0	23.86	14.74
46,000	0	5.8	58.6	24.56	14.71
46,000	200	5.9	60.6	21.08	16.34
46,000	400	5.8	57.8	32.07	13.20

TABLE 13. Effects of phosphate applications on the exchangeable calcium values in the Kaumoali series plots receiving 30,000 pounds lime per acre, island of Hawaii

APPLIED P_2O_5, POUNDS PER ACRE	KAUMOALI SERIES PLOTS, PAAUHAU PLANTATION, RECEIVING 30,000 POUNDS LIME PER ACRE
	Exchangeable Ca, me/100 gm
0	12.00[b]*
200	12.81[b]
400	22.86[a]

* Where different letters are used, the values differ significantly according to Duncan's (*28*) multiple range test.

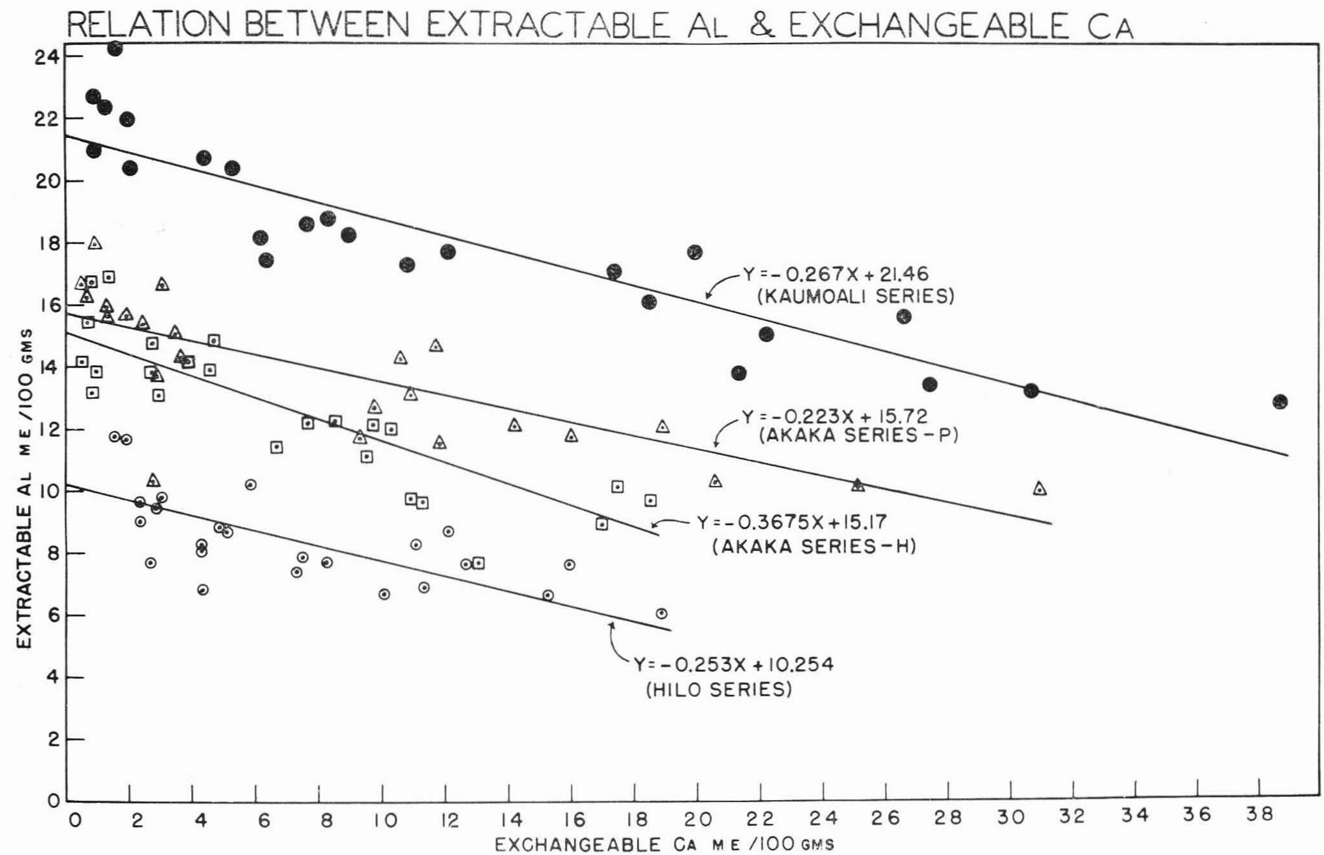

FIG. 2. Relationship between extractable aluminum and exchangeable calcium, 5 months after installation of experimental field plots, in soils of the Hilo series, Hilo plantation; Akaka series, Hakalau plantation and Pepeekeo plantation; and Kaumoali series, Paauhau plantation, island of Hawaii.

TABLE 14. Correlation coefficients of exchangeable calcium–extractable aluminum relationships for field plot soils of Hilo series, Akaka series, and Kaumoali series, island of Hawaii

SOIL SERIES	PLANTATION	CORRELATION COEFFICIENT, r VALUE
Hilo	Hilo	–0.76**
Akaka	Hakalau	–0.86**
	Pepeekeo	–0.82**
Kaumoali	Paauhau	–0.91**

** Significant at or beyond the 1% level. n = 24, for each plantation.

TABLE 15. Correlation coefficients and regression factors of pH and logarithm of exchangeable calcium relationships for field plot soils of Hilo series, Akaka series, and Kaumoali series, island of Hawaii

SOIL SERIES	PLANTATION	CORRELATION COEFFICIENT, r VALUE	REGRESSION FACTORS	
			α	β
Hilo	Hilo	0.90**	–3.61	0.76
Akaka	Hakalau	0.95**	–3.13	0.90
	Pepeekeo	0.95**	–4.46	1.07
Kaumoali	Paauhau	0.87**	–3.98	1.08

** Significant at or beyond the 1% level. n = 24, for each plantation.

TABLE 16. Correlation coefficients and regression factors of pH–extractable aluminum relationships for field plot soils of Hilo series, Akaka series, and Kaumoali series, island of Hawaii

SOIL SERIES	PLANTATION	CORRELATION COEFFICIENT, r VALUE	REGRESSION FACTORS	
			α	β
Hilo	Hilo	–0.54**	20.5	–2.10
Akaka	Hakalau	–0.80**	33.2	–3.85
	Pepeekeo	–0.76**	35.0	–3.66
Kaumoali	Paauhau	–0.87**	52.5	–6.34

** Significant at or beyond the 1% level. n = 24, for each plantation.

There were no situations in which the heavy applications of lime had a detrimental effect on the growth of sugar cane.

Discussion

Heavy applications of crushed coral resulted in substantial reductions in extractable aluminum, accompanied by an increase in exchangeable calcium. Where there is an appreciable amount of aluminum in a form that is liable to affect plant growth adversely, heavy applications of lime are probably necessary before a substantial modification of this element can be obtained.

Highly significant negative correlations were found between extractable aluminum and soil pH and between extractable aluminum and exchangeable calcium in the soils of all the experimental plots. Highly significant positive correlations for all experimental plot soils were found for soil pH and exchangeable calcium values expressed as logarithms. In his studies of soils from various localities within a humid tropical region, Popenoe (*85*) reported similar relationships between soil pH, exchangeable calcium, and exchangeable aluminum. However, Popenoe obtained curvilinear relationships for soil pH–exchangeable aluminum, and exchangeable calcium–exchangeable aluminum, as well as for pH–exchangeable calcium. These three soil properties are very closely associated with one another, and any attempt to separate their effects under field conditions meets with difficulty.

Fieldes *et al.* (*31*) concluded from studies of highly amorphous soils of the Cook Islands that the principal exchange material is amorphous hydrous aluminum oxide. Similarly, the high content of amorphous hydrated aluminum compounds of the Hawaiian soils would contribute considerably to their high cation exchange capacities. It is of interest that the applied coral did not significantly alter the magnitude of the cation exchange capacity in any situation in the Hawaiian soils. This phenomenon indicates that the reduction in extractable aluminum was not associated with any modification of the cation exchange capacity. It appeared that the addition of 22,000 pounds crushed coral per acre to the soils of the Hilo series produced an environment which, with increased phosphate additions, resulted in an increase in cation exchange capacity.

The evidence of substantial reductions in extractable aluminum, resulting from liming, introduces the question of the fate of this element. Downward movement of soluble aluminum within the soil profile could have occurred; however, because of the high total aluminum content, the equilibrium between colloidal aluminum and soluble aluminum would be of importance in these soils. This equilibrium would be governed principally by degree of soil acidity. Trenel (*114*) states that the formation of soluble aluminum, by the effect of NH_4 or K salts, is explained by the equation: $Al(OH)_3 + 3KCl = AlCl_3 + 3KOH$. He also states that the formation of $AlCl_3$ is favored when in the presence of silicic acid gel or humus gels lacking bases. Silicic acid gels and humic gels lacking bases are presumed to be plentiful in the Hawaiian soils. Thus, a downward movement of soluble aluminum would probably not be of lasting benefit if the equilibrium is such that additional aluminum is contributed to the soil solution. A shift in equilibrium away from the ionic forms of aluminum to the complexed and polymerized forms as described by Brosset (*7*, *8*) is envisaged. Extreme modification of this material could lead to an increase in crystallinity. X-ray diffraction patterns showed gibbsite peaks in all the soils that were studied; soils of the Akaka series had the largest peak and soils of the Kaumoali series, the smallest. No increase in crystallinity due to liming was recorded for these soils, and if such a phenomenon was taking place, the time period of approximately 5 months must have been too brief for this effect to develop and be measured by such methods, or the material could have been in a cryptocrystalline condition, and therefore undetectable by X-ray methods.

For each soil series studied, there was a high degree of correlation between pH and extractable aluminum. In his studies of the nature of pH, Raupach (*89*) considered that aluminum ions of varying valence may be involved as the pH rises. Magistad (*56*) and Schmehl *et al.* (*96*) found a significant decrease in aluminum which is harmful to plants occurred with an increase in pH values from just below 5.0 to above 5.0. On the other hand, Moskal (*72*) found a correlation only between mobile aluminum concentration and exchange acidity, and none between mobile aluminum and the pH levels, whether or not they were measured in H_2O or KCl.

Throughout this study it appeared that there was a relationship between extractable aluminum and buffer capacity. The highest extractable aluminum contents were found in the soils of the Kaumoali series and they also required the highest coral applications to bring the soil pH to the anticipated value of 7.0. Schofield, as reported by Russell (*93*), has shown that the buffer curve of an acid soil is dependent on aluminum. In view of the much lower rainfall at the location of the experimental plots for the Kaumoali series, the very high extractable aluminum value for the soil of this series was surprising. In his studies on widely separated acid soils, Burgess (*9*) recorded the highest "active" aluminum figure, that he obtained, for a soil from Honokaa Sugar Company. This plantation is adjacent to Paauhau plantation.

It is difficult to explain the significant decrease in exchangeable calcium with applied phosphate that occurred in the Pepeekeo experimental plots receiving 34,000 pounds lime per acre. Phosphate sorption by calcium carbonate, as described by Cole *et al.* (*20*), is offered as a possible explanation. The resultant reduced rate of reaction between lime and soil may have reduced the amount of calcium entering the exchange complex. On the other hand, the 400 pounds phosphate application significantly increased the exchangeable calcium in the plots of the Kaumoali series which had received 30,000 pounds lime per acre.

It is of interest to note that any modification in soil properties due to applied phosphate was confined within a particular level of lime treatment.

Long-term effects of treatment on test soils

In an attempt to learn how long these chemical modifications of the test soils would endure or what subsequent changes might occur, further samples were taken at approximately 1- and 2-year intervals after installation of the experimental plots. In these further studies, the phosphate-treated plots were omitted and attention was given entirely to the lime-treated plots. The chemical analysis and procedures were the same as for the previous samples.

Results

The soil samples collected at approximately 1- and 2-year intervals after installation of the experimental field plots are hereafter referred to as the 1-year and 2-year samples. The previously described liming response patterns of increased exchangeable calcium and pH values, and decreased extractable aluminum values, were maintained for both samples. The relationships between exchangeable calcium and extractable aluminum values for these samples are presented in figures 3 and 4, respectively. Cation exchange capacity values were not determined for the 1-year samples. Table 17 presents the correlation coefficients and regression factors for soil pH and extractable aluminum relationships for both samples, and table 18, correlation coefficients and regression factors for the logarithmic value of exchangeable calcium and soil pH relationships. In calculating the regression values, x = pH value.

TABLE 17. Correlation coefficients and regression factors of pH and extractable aluminum relationships for field plot soils of Hilo series, Akaka series, and Kaumoali series, island of Hawaii, 1 year and 2 years after installation

SOIL SERIES	PLANTATION	TIME ELAPSED SINCE INSTALLATION	CORRELATION COEFFICIENT, r VALUE	REGRESSION FACTOR	
				α	β
Hilo	Hilo	1 year	−0.63	24.9	−2.72
		2 years	−0.70	33.7	−4.16
Akaka	Hakalau	1 year	−0.56	31.5	−2.70
		2 years	−0.78*	43.8	−5.37
	Pepeekeo	1 year	−0.81*	38.6	−3.67
Kaumoali	Paauhau	1 year	−0.90**	63.2	−7.38
		2 years	−0.78*	44.8	−4.75

* Significant at the 5% level. n = 8, for each plantation.
** Significant at or beyond the 1% level.

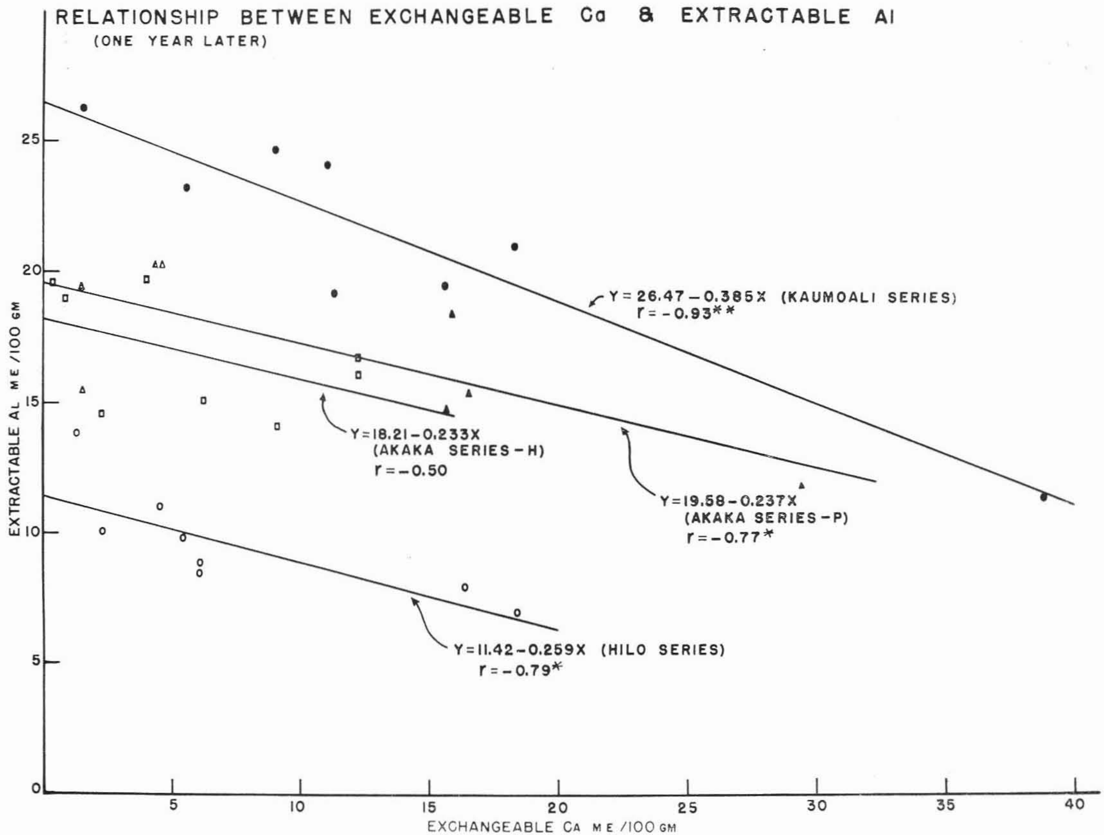

FIG. 3. Relationship between extractable aluminum and exchangeable calcium, 1 year after installation of experimental field plots, in soils of the Hilo series, Hilo plantation; Akaka series, Hakalau plantation and Pepeekeo plantation; and Kaumoali series, Paauhau plantation, island of Hawaii.

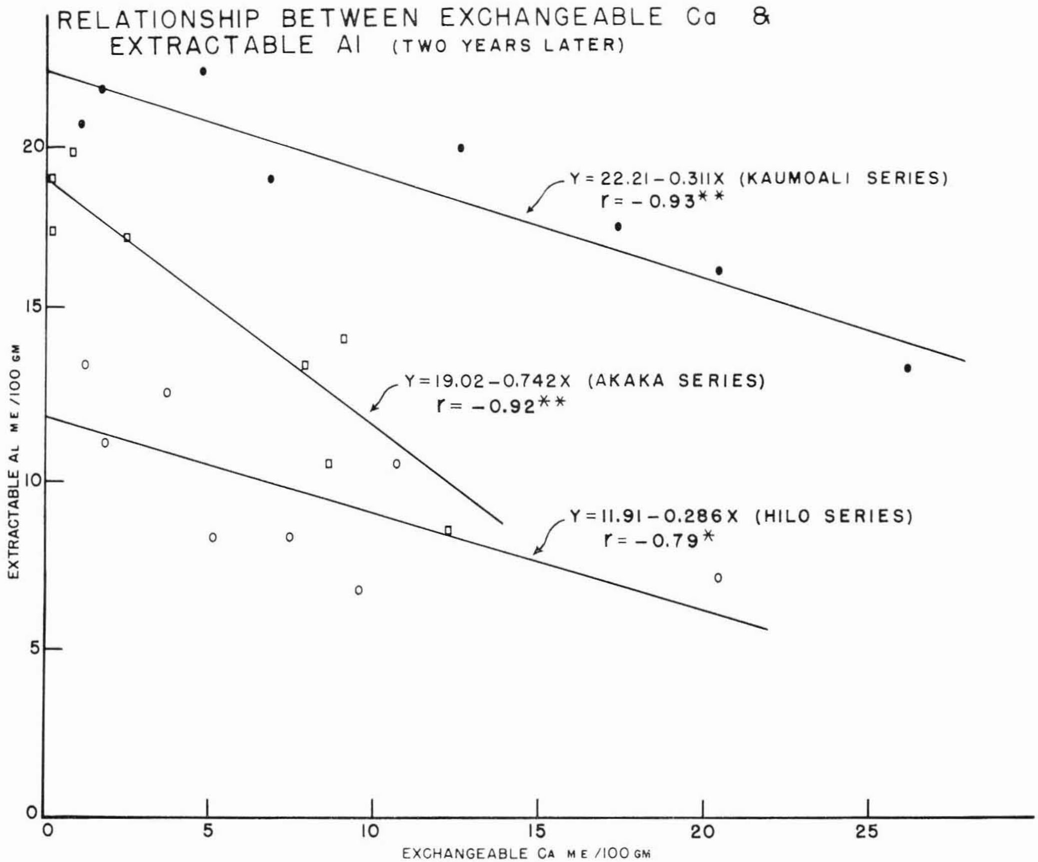

FIG. 4. Relationship between extractable aluminum and exchangeable calcium, 2 years after installation of experimental field plots, in soils of the Hilo series, Hilo plantation; Akaka series, on Hakalau plantation; and Kaumoali series, Paauhau plantation, island of Hawaii.

TABLE 18. Correlation coefficients and regression factors of pH and logarithmic exchangeable calcium relationships for the field plot soils of Hilo series, Akaka series, and Kaumoali series, island of Hawaii, 1 year and 2 years after installation

SOIL SERIES	PLANTATION	TIME ELAPSED SINCE INSTALLATION	CORRELATION COEFFICIENT, r VALUE	REGRESSION FACTOR α	β
Hilo	Hilo	1 year	0.84**	—3.42	0.73
		2 years	0.86**	—4.01	0.95
Akaka	Hakalau	1 year	0.98**	—5.75	1.16
		2 years	0.96**	—6.36	1.46
	Pepeekeo	1 year	0.94**	—3.28	0.69
Kaumoali	Paauhau	1 year	0.95**	—2.90	0.68
		2 years	0.91**	—4.17	0.92

** Significant at or beyond the 1% level. n = 8, for each plantation.

TABLE 19. Exchangeable calcium, pH, and extractable aluminum values for lime-treated Hilo series plots, Hilo plantation, island of Hawaii, 14 months after installation

CORAL, lb/acre	PLOT NO.	pH	EXCHANGEABLE Ca, me/100 gm	EXTRACTABLE Al, me/100 gm
0	34	5.5	1.32	13.51
0	42	5.1	2.23	9.91
4,000	12	5.5	6.05	8.32
4,000	20	5.5	4.52	10.90
11,000	3	5.6	5.43	9.65
11,000	9	5.5	6.09	8.71
22,000	17	6.3	16.39	7.80
22,000	27	6.4	18.40	6.83

Hilo series

Results of the chemical analysis for the 1- and 2-year samples of soils of the Hilo series from Hilo plantation are presented in tables 19 and 20.

TABLE 20. Exchangeable calcium, pH, cation exchange capacity, and extractable aluminum values for lime-treated Hilo series plots, Hilo plantation, island of Hawaii, 26 months after installation

CORAL, lb/acre	PLOT NO.	pH	CATION EXCHANGE CAPACITY, me/100 gm	EXCHANGEABLE Ca, me/100 gm	EXTRACTABLE Al, me/100 gm
0	34	5.5	58.6	0.56	13.55
0	42	5.1	56.5	1.00	11.13
4,000	12	5.6	58.6	2.88	8.28
4,000	20	5.7	58.5	1.72	12.65
11,000	3	6.0	60.0	5.32	6.75
11,000	9	5.8	61.7	3.92	8.27
22,000	17	5.9	56.7	5.84	10.42
22,000	27	6.4	55.0	10.36	7.06

The pH values show a slight change when the 1- and 2-year samples are compared. The cation exchange capacity values show no modifications due to liming. Compared with the 1-year samples, the 2-year samples indicate there was a decrease in exchangeable calcium accompanied by an increase in extractable aluminum values. Mean exchangeable calcium values for each liming rate for the 1- and 2-year samples, and for a sampling at 5 months, are presented in figure 5.

Akaka series

Results of the chemical analysis for the 1- and 2-year samples of soils of the Akaka series from Hakalau plantation are presented in tables 21 and 22. After 2 years, there was a general reduction in soil pH values for all levels of applied lime. There was also a steady reduction in exchangeable calcium over the 2-year period, and this is illustrated in figure 6. The trend towards reduced cation exchange capacity values with each liming increment was not significant.

Results of the chemical analysis for the 1-year samples of the soils of the Akaka series from Pepeekeo plantation are presented in table 23. Soil pH values were greater at Pepeekeo plantation than at Hakalau plantation. As a result of the heaviest lime application, one of the Pepeekeo plots had a pH of 7.0. Although the calcium values at Pepeekeo plantation were higher than at Hakalau plantation, the general response pattern for the two plantations was similar.

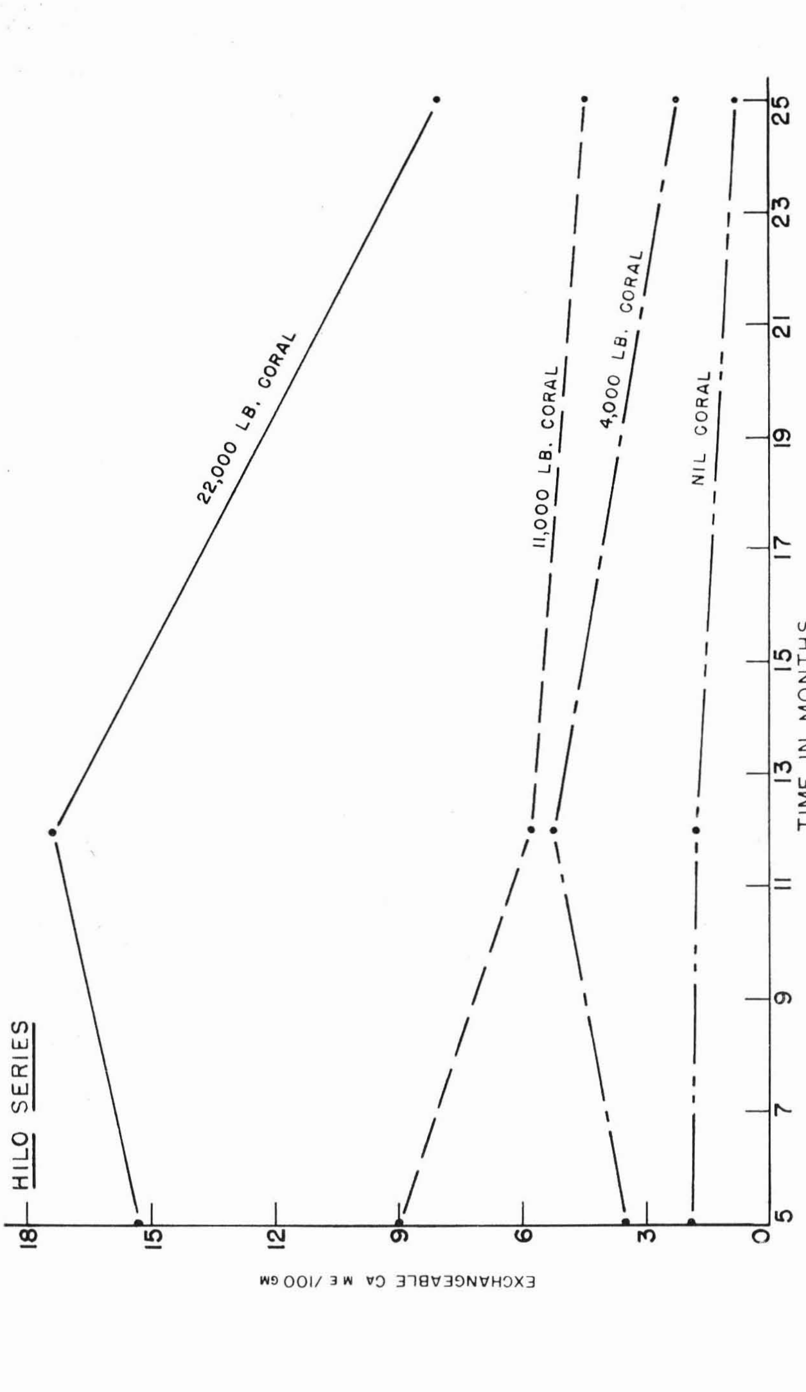

FIG. 5. Progressive changes in mean exchangeable calcium values, over a 2-year period, for the liming levels used in Hilo series experimental field plots, Hilo plantation, island of Hawaii.

TABLE 21. Exchangeable calcium, pH, and extractable aluminum values for lime-treated Akaka series plots, Hakalau plantation, island of Hawaii, 14 months after installation

CORAL, lb/acre	PLOT NO.	pH	EXCHANGEABLE Ca, me/100 gm	EXTRACTABLE Al, me/100 gm
0	20	4.9	0.82	18.99
0	23	4.7	0.38	19.64
4,000	14	5.1	2.26	14.56
4,000	17	5.4	3.97	19.69
11,000	2	5.6	6.22	15.05
11,000	5	5.9	12.33	16.68
22,000	8	5.8	9.16	14.03
22,000	11	6.0	12.35	16.00

TABLE 22. Exchangeable calcium, pH, cation exchange capacity, and extractable aluminum values for lime-treated Akaka series plots, Hakalau plantation, island of Hawaii, 26 months after installation

CORAL, lb/acre	PLOT NO.	pH	CATION EXCHANGE CAPACITY, me/100 gm	EXCHANGEABLE Ca, me/100 gm	EXTRACTABLE Al, me/100 gm
0	20	4.6	67.2	0.20	17.51
0	23	4.7	67.5	0.20	19.08
4,000	14	4.9	60.5	0.83	19.87
4.000	17	5.3	65.5	2.51	17.12
11,000	2	5.5	49.9	8.63	10.49
11,000	5	5.7	64.2	7.99	13.41
22,000	8	5.6	61.9	8.53	12.33
22,000	11	5.9	52.2	9.19	14.22

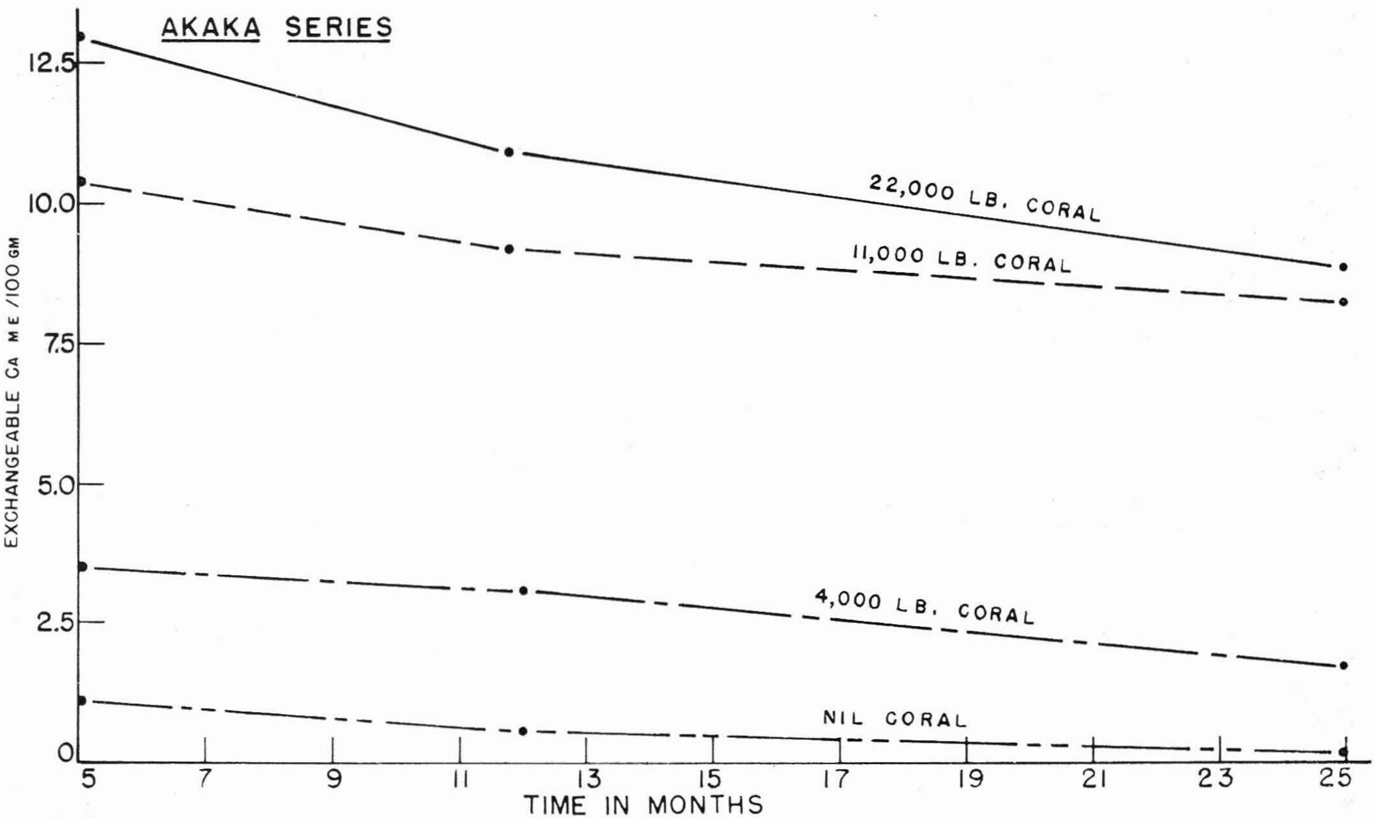

FIG. 6. Progressive changes in mean exchangeable calcium values, over a 2-year period, for the liming levels used in Akaka series experimental field plots, Hakalau plantation, island of Hawaii.

TABLE 23. Exchangeable calcium, pH, and extractable aluminum values for lime-treated Akaka series plots, Pepeekeo plantation, island of Hawaii, 10 months after installation

CORAL, lb/acre	PLOT NO.	pH	EXCHANGEABLE Ca, me/100 gm	EXTRACTABLE Al, me/100 gm
0	8	5.4	1.56	15.47
0	30	5.1	1.50	19.44
4,000	3	5.5	4.56	20.25
4,000	27	5.3	4.38	20.21
19,000	12	6.2	15.90	18.29
19,000	31	6.4	16.58	15.25
34,000	10	6.4	15.71	14.74
34,000	26	7.0	29.49	11.75

Kaumoali series

Results of the chemical analysis for the 1- and 2-year samples of soils of the Kaumoali series from Paauhau plantation are presented in tables 24 and 25. Both the 1- and 2-year samples showed little change in pH and exchangeable calcium values. Mean exchangeable calcium values for the 1- and 2-year samples, and for a sampling at 5 months, are presented in figure 7.

TABLE 24. Exchangeable calcium, pH, and extractable aluminum values for lime-treated Kaumoali series plots, Paauhau plantation, island of Hawaii, 12 months after installation

CORAL, lb/acre	PLOT NO.	pH	EXCHANGEABLE Ca, me/100 gm	EXTRACTABLE Al, me/100 gm
0	11	4.9	1.61	26.24
0	23	5.1	5.57	23.22
12,000	1	5.5	9.07	24.64
12,000	16	5.7	11.36	19.08
30,000	6	5.7	11.17	24.00
30,000	17	6.0	15.64	19.38
46,000	8	6.0	18.29	20.90
46,000	20	6.7	38.82	11.39

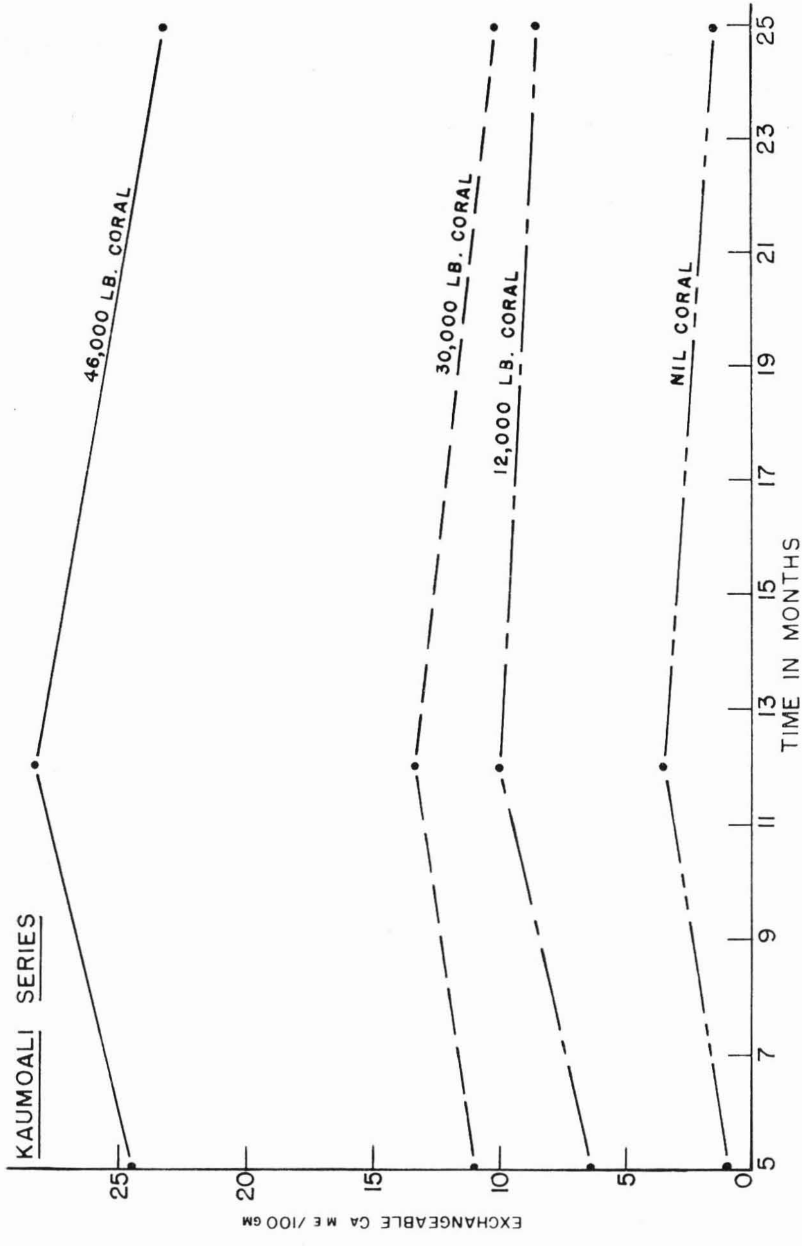

FIG. 7. Progressive changes in mean exchangeable calcium values, over a 2-year period, for the liming levels used in Kaumoali series experimental field plots, Paauhau plantation, island of Hawaii.

TABLE 25. Exchangeable calcium, pH, cation exchange capacity, and extractable aluminum values for the lime-treated Kaumoali series plots, Paauhau plantation, island of Hawaii, 24 months after installation

CORAL, lb/acre	PLOT NO.	pH	CATION EXCHANGE CAPACITY, me/100 gm	EXCHANGEABLE Ca, me/100 gm	EXTRACTABLE Al, me/100 gm
0	11	5.2	68.6	1.70	21.71
0	23	4.7	65.5	1.08	20.64
12,000	1	5.0	76.8	4.80	22.20
12,000	16	5.7	69.6	12.74	19.90
30,000	6	5.7	67.2	13.82	17.45
30,000	17	5.4	63.1	6.83	19.01
46,000	8	6.2	65.3	20.48	16.18
46,000	20	5.9	66.6	26.21	13.27

Discussion

The mean exchangeable calcium values presented in figures 5, 6, and 7 illustrate the response of these soils to liming over a 2-year period. In the Kaumoali series, the highest values were obtained in the 1-year samples, but both the 5-month and 2-year samples also had high values for exchangeable calcium. In the Akaka series, the highest exchangeable calcium values were found in the 5-month samples; after this period there was a continuous reduction in values for all levels of applied lime. The response of Hilo series samples was intermediate between the responses of the other two soil series.

The calcium-aluminum relationships remained relatively constant throughout the 2-year period for the soils of both the Hilo and Kaumoali series. For the first year, this relationship in the Akaka series was similar to those of the other two series, but the linear regression gradient increased markedly in the 2-year samples of this soil series.

The observations illustrated in figures 3 through 7 demonstrate that soils of the Akaka series do not have as great a capacity to retain exchangeable calcium as do the soils of the other two series. The decline in exchangeable calcium over the 2-year period in the Akaka soils was accompanied by a reduction of soil pH values. In view of these established trends, it would appear unlikely that any appreciable increase would occur in pH in the experimental plots for this soil series.

It also appeared that the progress of calcium release in limed soils governs the rate at which they resume their prelimed condition. Thus the persistence of effects of heavy lime applications to such soils is dependent principally on their calcium-retaining powers. Apparently the soils of the

Akaka series, in comparison to the soils of the other two series, have an acidic property which is of greater intensity. Chizhevskii and Korovkin (*16*) considered that soils with a high exchange acidity due mainly to available aluminum are in particular need of lime. Hardy (*41*) concluded that the "potent acid-forming agent" in the upland soils derived from volcanic ash on the island of Dominica was possibly due to hydrolyzable compounds of aluminum and iron. A comparison of extractable aluminum values for the three Hawaii soil series indicates that this property is not directly related to the intensity of soil acidity. Schofield (*98*) found that for certain strongly acid soils high in sesquioxides the basic positive charges exceed the permanent negative charge combined with the acidic negative charges. Schofield suggested that such soils retain anions but not cations. A subsequent experiment by Rixon (*91*) with the Hawaii soils showed that a much greater contribution of aluminum to percolating water was made by the soils of the Akaka series than was made by the soils of either the Hilo or Kaumoali series. It is suggested that the clearly pronounced inherent acidity of the soils of the Akaka series is due principally to hydrolyzable aluminum compounds.

The rate of lime application is usually determined by the buffering capacity and the initial pH of the soil. However, these measurements do not necessarily indicate the persistence of the effects resulting from lime applied to highly hydrated, amorphous soils. The data from these investigations denote that there is some inherent factor that influences the persistence of liming. This factor could be called inherent acidity.

SUMMARY

A series of replicated field trials, using four levels of lime with three levels of phosphate superimposed across the lime levels, was established in the high-rainfall regions of the island of Hawaii. The phosphate was applied at levels of nil, 200, and 400 pounds P_2O_5 per acre. Lime applications in the form of crushed coral stone were heavy, corresponding to the high buffering capacity of the amorphous soils. The heaviest of the coral applications was expected to produce a pH of 7.0 in the soils. Three soil series were used; namely, the Akaka and Hilo, which are Hydrol Humic Latosols, and the Kaumoali, a Humic Latosol. These soils are presently used for sugar cane production. The heaviest coral application applied to the Hilo series was at 22,000 pounds per acre; it was applied also to one of the two areas of the Akaka series. The other area of Akaka soil received 34,000 pounds crushed coral per acre, and the Kaumoali series, 46,000 pounds crushed coral per acre.

Soil samples were taken and analyzed approximately 5 months after the installation of these experimental areas. With heavy lime applications, the following results were obtained:

1. There was a general increase in pH, but even the heaviest applications of crushed coral did not achieve neutrality.

2. An increase in exchangeable calcium was accompanied by a decrease in extractable aluminum. This relationship was highly significant for each of the soils.
3. Highly significant negative correlations between extractable aluminum and pH and positive correlations between logarithmic calcium values and pH were found.
4. No evidence of a significant alteration of the cation exchange capacity, due directly to liming, was obtained for any soil.

Any significant modification due to phosphate application was confined to a particular level of applied crushed coral. There was a significant increase in cation exchange capacity with each addition of phosphate to the soils of the Hilo series which had received 22,000 pounds coral per acre. For the soils of the Akaka series on Pepeekeo plantation, each increase in added phosphate produced a decrease in exchangeable calcium in the plots which had received 34,000 pounds coral per acre. The decrease in exchangeable calcium produced by the application of phosphate at 400 pounds per acre in the Pepeekeo plots was significant. A significant increase in exchangeable calcium was obtained with the application of phosphate at 400 pounds per acre to the soils of the Kaumoali series which had received 30,000 pounds coral per acre.

Additional soil samples were taken at 1- and 2-year intervals after the installation of the field plots. Analysis of these samples indicated that the chemical modifications of the soils persisted in these experimental plots. The response pattern of increased exchangeable calcium and pH values and decreased extractable aluminum values due to liming were maintained over the 2-year period with some modifications. The tendency towards a decrease in cation exchange capacity was not significant in the 2-year samples of the soils of the Akaka series. There was no appreciable change in cation exchange capacity for the other soil series. Linear relationships between exchangeable calcium and extractable aluminum were demonstrated.

The pattern of change with time for mean exchangeable calcium values was taken as an indication of the persistence of liming effects. The highest exchangeable calcium values for the soils of the Kaumoali series were found in the 1-year samples; for the Akaka series, in the 5-month samples; and values for the Hilo series were intermediate between these two series. It was concluded that the persistence of liming effects in these soils is governed by their ability to retain calcium. The release of calcium is thought to be dependent on an inherent property of the soils, and it is suggested that this property be called inherent acidity.

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